Full Solar Spectrum Photovoltaic Materials Identified

A team led by Wladek Walukiewicz, working with researchers at Cornell University, and Ritsumeikan University, Japan, has discovered that, contrary to earlier reports, the band gaps of the $In_{1-x}Ga_xN$ ternary alloy system extend over a very wide energy range (0.7 eV to 3.4 eV) and thus provide a near-perfect match to the solar energy spectrum. This creates the opportunity to design and fabricate new multijunction solar cells that will have greatly improved efficiencies, possibly reaching the theoretically predicted ultimate efficiencies.

The power conversion efficiency limit for a solar cell based on a single semiconducting material is 31%. The primary reason for this limit is that no one material can perfectly match the broad range of solar radiation, which has usable energy in the photon range of 0.4 – 4 eV (see figure). Light with energy below the bandgap of the semiconductor will not be absorbed and thus not be converted. Light with energy above the bandgap will be absorbed, but the excess energy above the bandgap will be lost in the form of heat. Decades of research in developing single-material solar cells has led to cell efficiencies close to the theoretical limit; the best cell of this type has an efficiency of 25.1%.

It was realized quite early that still higher efficiencies could be achieved by using stacks of semiconductors with different band gaps. In this design, the higher gap materials convert higher energy photons, but do not absorb lower energy photons which then pass through to the lower gap materials. Maximum, theoretically predicted efficiencies increase to 50%, 56%, and 72% for stacks of 2, 3, and 36 junctions with appropriately optimized energy gaps, respectively. Indeed, tandem solar cells with as many as three semiconductors have been developed over the last decade and such cells currently have the highest efficiency achieved; about 30%.

A major challenge in achieving widespread use of these multijunction solar cells lies in the identification of materials with the appropriate bandgaps. The 50% efficient 2 junction cell requires an upper cell bandgap of 1.7 eV and a lower cell gap of 1.1 eV. The two-layer tandem cells grown to date are less efficient, using the best available 1.85/1.43 eV band gap combination that takes advantage of the lattice match of $Ga_{0.5}In_{0.5}P$ and GaAs. Fabrication of 1.7/1.1 eV band gap cells would be simplified if two materials in a single ternary alloy system could be used, but it was believed that there was no suitable system with direct bandgaps in this optimal range.

Working with crystal growers from Cornell and Ritsumeikan University, Japan, the LBNL team performed optical tests (absorption and "photoluminescence") on a wide range of extremely high quality InN and $In_xGa_{1-x}N$ films grown under carefully controlled conditions. It was found that the direct band gap of pure InN is 0.7 eV rather than the previously reported 2.0 eV, which had been measured in lower quality material. Furthermore, it was shown that alloying the InN with GaN to form $In_xGa_{1-x}N$ can produce materials whose bandgaps can be continuously varied from 0.7 eV to 3.4 eV. This single semiconductor alloy system, therefore, has an almost perfect match to the entire solar spectrum. Not only does this range include the optimal bandgap values (1.1 and 1.7 eV) for a two-layer cell, it will also enable the fabrication of optimized tandem cells with more layers, for which materials whose band gaps extend close to the lower and nearly all the way to the upper bounds of the usable region of the solar spectrum are required. More recent work has shown that the $In_xAl_{1-x}N$ system has direct band gaps spanning an even wider energy range: from 0.7 – 6.2 eV; thus, this related materials system may be useful for both solar energy conversion and for other optoelectronic applications in the near-IR to deep ultraviolet regions of the spectrum

Although grown on lattice mismatched substrates, all the $In_xGa_{1-x}N$ films show an exceptionally strong and robust photoluminescence, demonstrating insensitivity of the optoelectronic properties to structural imperfections. This observation bodes very well for applications of these materials in environmentally harsh conditions. To fully implement the $In_xGa_{1-x}N$ alloys for photovoltaic applications some additional hurdles such as control of p-type doping must be overcome, however the work demonstrates that III-V nitride alloys are promising candidates for the development of new solar cells with efficiencies as high as 50%. Furthermore, the discovery extends the range of potential optoelectronic applications of III-V nitride alloys from the near infrared to the deep ultraviolet spectral regions.

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